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A NEW MEASUREMENT OF THE PRIMORDIAL ABUNDANCE OF DEUTERIUM: TOWARDS CONVERGENCE WITH THE BARYON DENSITY FROM THE CMB?[1]

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ABSTRACT

From the analysis of the near-UV spectrum of the QSO 2206−199, obtained with a long series of exposures with STIS on the *HST*, we deduce a value D/H $= (1.65 \pm 0.35) \times 10^{-5}$ (1σ error) for the abundance of deuterium in the $z_{\rm abs} = 2.0762$ damped Lyman α system (DLA) along this sight-line. The velocity structure of this absorber is very simple and its neutral hydrogen column density, N(H I), is accurately known; the error in D/H is mostly due to the limited signal-to-noise ratio of the spectrum. Since this is also one of the most metal-poor DLAs, with metal abundances $\sim 1/200$ of solar, the correction due to astration of D is expected to be insignificant and the value we deduce should be essentially the primordial abundance of deuterium. When all (six) available measurements of D/H in high redshift QSO absorbers are considered, we find that the three DLAs—where N(H I) is measured most reliably—give consistently lower values than the three Lyman limit systems. We point out that the weighted mean of the DLA measurements, D/H $= (2.2 \pm 0.2) \times 10^{-5}$, yields a baryon density $\Omega_B h^2 = 0.025 \pm 0.001$ which is within $\sim 1\sigma$ of the value deduced from the analysis of the CMB angular power spectrum, and is still consistent with the present-day D/H and models of Galactic chemical evolution. Future observations of D I absorption in other DLAs are needed to establish whether our finding reflects a real advantage of DLAs over other classes of QSO absorbers for the measurement of D, or is just a statistical fluctuation.

Subject headings: quasars: absorption lines — quasars individual (Q2206−199) — cosmology: observations — nuclear reactions, nucleosynthesis, abundances

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1. Introduction

Among the light elements created in the Big Bang, deuterium is the one whose abundance depends most sensitively on the baryon-to-photon ratio, η, which can in turn be related to the cosmological density of baryons Ω_B, through the known temperature of the cosmic microwave background (CMB). It was realized 25 years ago (e.g. Adams 1976) that QSO absorption line systems at high redshift would provide the most direct avenue to a precise determination of the primordial abundance of deuterium, avoiding the need to account for its subsequent destruction through successive cycles of star formation in galaxies (astration). However, we have had to wait until the advent of 8-10 m telescopes, equipped with efficient high resolution spectrographs, to realize those early expectations.

The reason is simple. The isotope shift between the D and H components of the Lyman series amounts to only $-82\,\mathrm{km\ s^{-1}}$; the vast majority of QSO absorption systems span or exceed this velocity range so that features due to D (less abundant than H by a factor of a few times 10^4) are normally blended with other, generally stronger, neutral hydrogen absorption components within the same complex. In order to find the rare absorbers with the simplest velocity structure it is necessary to reach down the QSO luminosity function to magnitudes which are only accessible with the light gathering power of the largest telescopes. Thus, nearly ten years since the commissioning of the Keck high resolution echelle spectrograph (HIRES; Vogt 1992) and five years since the first detection of D I absorption in a QSO spectrum (Tytler, Fan, & Burles 1996), the available body of data on the primordial abundance of D is still frustratingly small, amounting to only five measures (Kirkman et al. 2001, also reviewed below). In contrast, determinations of the He/H ratio—far more accessible than D/H but much less sensitive to Ω_B—number in the many tens (see Pagel 2000 for a recent review).

Until recently, only Lyman limit systems (LLS)—absorbers with neutral hydrogen column densities $N(\mathrm{H\ I}) \geq 3 \times 10^{17}\,\mathrm{cm^{-2}}$—had been targeted in searches for interstellar deuterium at high redshift. The rarer damped Lyman α systems (DLAs), with $N(\mathrm{H\ I}) \geq 2 \times 10^{20}\,\mathrm{cm^{-2}}$, potentially offer significant advantages over LLS. First and foremost, the neutral hydrogen column density can be measured more precisely than is normally the case for LLS. The combination of the width of the saturated core and damping wings of the Lyman α absorption line usually constrain $N(\mathrm{H\ I})$ to within 10% or better, even in moderate resolution spectra (e.g. Pettini et al. 1997). Second, a knowledge of the degree of metal enrichment of the QSO absorber is required to relate the measured D/H ratio to the primordial value. In DLAs the metallicity of the gas can be determined straightforwardly and with good precision, without recourse to the uncertain, and often large, ionization correction required for LLS (e.g. Viegas 1995). Thirdly, the probability of blending with 'interloper' H I clouds is much reduced for DLAs, given the steep slope of the $N(\mathrm{H\ I})$ distribution (Péroux et al. 2001), and D absorption should be detectable in many higher order Lyman lines, rather than in just the first few transitions in the series.

In principle, we know of no reason why the velocity structure of DLAs should be systematically more complex than that of LLS—one could in fact argue that the opposite is more likely to be the case, if DLAs are formed in the inner regions of protogalactic disks while LLS arise in more extended halo regions (e.g. Steidel 1993). Furthermore, there is mounting evidence, both observational (e.g. Pettini et al. 1999 and references therein) and theoretical (e.g. Mo, Mao, & White 1998; Jimenez, Bowen, & Matteucci 1999) that DLAs may trace preferentially galaxies with low rates of star formation, where astration of D is also likely to have been low. In any case, we believe that DLAs are no less suitable than LLS in the search for high redshift D I absorption; they are just rarer and this explains why they have not figured as prominently up to now.

Among the well studied DLAs, the $z_{\rm abs} = 2.0762$ system in the bright (V = 17.3) $z_{\rm em} = 2.559$ QSO Q2206−199 is a prime candidate for showing resolved D I absorption. High resolution spectroscopy obtained initially with the University College London echelle spectrograph at the Anglo-Australian telescope (Pettini & Hunstead 1990) and later with HIRES on Keck (Prochaska & Wolfe 1997) showed that in this DLA all the metal lines from neutral gas apparently consist of a single, narrow component with a Doppler parameter $b = 5.7$ km s^{-1}. This is also one of the lowest metallicity DLAs known, with different elements being underabundant relative to solar by factors between 170 (Si) and 420 (Fe). Given the minimal amount of chemical enrichment experienced by the interstellar medium of this absorber, we could reasonably expect its deuterium abundance to be very close to the primordial value.

At the high column densities of DLAs, the D and H components are saturated and blended together in the strongest lines of the Lyman series. In order to resolve the two isotopes, it is necessary to access high order transitions; at $z_{\rm abs} = 2.0762$ all the lines of diagnostic value fall below the atmospheric cut-off at 3100 Å and are not accessible from the ground. For this reason in December 1996 we were awarded 31 orbits of the *Hubble Space Telescope* to record the near-UV spectrum of Q2206−199 with STIS (the Space Telescope Imaging Spectrograph). For a variety of reasons the full set of observations was only completed four years later, in September 2000. In this paper we present the resulting co-added spectrum from which we obtain a new measurement of the deuterium abundance. In the mean time, D I absorption has been detected in another DLA, the $z_{\rm abs} = 3.0249$ system in Q0347−393, by D'Odorico, Dessauges-Zavadsky, & Molaro (2001) who used the Ultraviolet-Visual Echelle Spectrograph (UVES) on the Very Large Telescope (VLT) of the European Southern Observatory. Thus, the total number of D/H measures in high redshift QSO absorbers now stands at six; we briefly comment on the dispersion of these values and on what it may imply for an improved determination of the primordial abundance of deuterium.

2. Observations

The STIS spectra were recorded with the near-UV MAMA detector and G230M grating through the 52×0.2 arcsec long slit with 31 orbits spread over seven visits between November 13, 1998 and September 16, 2000. The total integration time was 82 490 s. The grating was set at a central wavelength $\lambda_c = 2818$ Å. With this configuration, the useful wavelength range recorded by the near-UV MAMA detector is 2773–2862 Å; in the rest frame of the $z_{\rm abs} = 2.0762$ DLA this corresponds to the interval 901.4–930.4 Å which includes all Lyman series lines from Ly7 to the Lyman limit. The resolution is 0.19 Å (20 km s^{-1} FWHM) sampled with 2.1 pixels.

The 31 STIS exposures were processed with the standard CALSTIS pipeline software. We extracted one-dimensional spectra from the fluxed and wavelength calibrated frames with the IRAF routine apall and then added them together after rebinning to a common wavelength scale. We found that the pipeline processing underestimates the scattered light in these low level exposures; consequently, we applied an empirical background correction of 5% of the continuum level in order to bring the cores of the saturated absorption lines to zero. Figure 1 shows the final spectrum, background subtracted, normalized to the QSO continuum, and reduced to the rest frame of the $z_{\rm abs} = 2.0762$ DLA. At the low light levels of the present observations the noise is dominated by the dark count of the NUV MAMA (which turned out to be significantly higher than pre-flight expectations and more than one hundred times higher than that of the FUV MAMA) and is roughly constant along the spectrum, irrespectively of the QSO signal. Its magnitude can be best appreciated from the fluctuations about the zero level in the cores of the strong saturated absorption lines near 927.5 and 923 Å and below the effective Lyman limit at 914 Å. In the continuum near Ly9 (see below) the signal-to-noise ratio is S/N $\simeq 10$.

3. Deuterium in the $z_{\rm abs} = 2.0762$ DLA

As can be appreciated from Figure 1, Q2206−199 exhibits a crowded spectrum at UV wavelengths. The QSO flux is absorbed by a multitude of features due to the Lyman α forest, the $z_{\rm abs} = 2.0762$ DLA, and a second DLA intercepted in this direction, at $z_{\rm abs} = 1.9205$, with much stronger and wider interstellar absorption lines (Pettini & Hunstead 1990; Prochaska & Wolfe 1997). For the present purposes we focus on the high order Lyman series of the $z_{\rm abs} = 2.0762$ DLA from Ly7 at 926.2257 Å to Ly13 at 916.429 Å; transitions to energy levels with $n \geq 14$ are so close in wavelength that they become blended with one another eventually producing an effective Lyman break near 914.5 Å. Figure 2 shows on an expanded scale six of the seven Lyman lines considered here. Three of them, Ly10, Ly11, and Ly13, are blended with other absorption features, as is Ly8 (shown in Figure 1). The remaining three lines, however, appear to be relatively free of contamination and D I absorption is clearly present in Ly7, Ly9, and Ly12. These are the three spectral features on which our measurement of N(D I) is based.

All the six Lyman lines in Figure 2 were fitted with Voigt profiles using the VPFIT package.[2] VPFIT returns the most likely values of redshift z, Doppler width b (km s^{-1}), and column

[2]VPFIT is available at http://www.ast.cam.ac.uk/~ rfc/vpfit.html

density N (cm^{-2}) by minimizing the difference between observed and computed profiles after convolution with the appropriate instrumental point spread function (PSF). We used the STIS PSF for the G230M grating supplied by the Space Telescope Science Institute; close to the line core the function is well approximated by a Gaussian with FWHM $= 20\,\mathrm{km\ s^{-1}}$ but its wings are significantly broader. In our fitting procedure we fixed the column density of neutral hydrogen to $N(\mathrm{H\ I}) = 2.73 \times 10^{20}$ cm^{-2} deduced from the profile of the damped Lyman α line (see §4 below), and the number of absorption components to one. All the metal absorption lines from H I gas in this DLA are best reproduced by a single absorption component at $z_{\mathrm{abs}} = 2.07623$ with Doppler parameter $b = 5.7\,\mathrm{km\ s^{-1}}$ (Prochaska & Wolfe 1997; Pettini et al. in preparation). Since the same value of b apparently applies to atoms spanning a range of atomic weight from 14 (N) to 56 (Fe), this velocity dispersion presumably reflects primarily turbulent, rather than thermal motions. Accordingly, we fixed $b_{\mathrm{turb}} = 5.0\,\mathrm{km\ s^{-1}}$ and let VPFIT solve for the thermal component, b_{th}, to the H I and D I Lyman lines; the results are collected in Table 1. The theoretical absorption profiles corresponding to the best solution returned by VPFIT are shown as continuous lines in Figure 2.

We deduce $\log N(\mathrm{D\ I}) = 15.65 \pm 0.1$ (1σ). The error is dominated by the modest signal-to-noise ratio of the STIS spectrum, rather than by systematic uncertainties in the continuum level or the details of the fitting procedure. We explored at length the effects of adopting different values of b_{turb}, varying the continuum level and $N(\mathrm{H\ I})$ by $\pm 1\sigma$, assuming a two-component model for the absorption lines[3], and in all cases VPFIT converged to values of $\log N(\mathrm{D\ I})$ which were well within the ± 0.1 dex uncertainty due to the noise in the spectrum. Figure 3 illustrates how the theoretical profiles obtained by lowering and increasing the value of $N(\mathrm{D\ I})$ by 2σ compare with the observed spectral lines in the two most sensitive cases, Ly9 and Ly12. The fits shown include absorption from adjacent components which are not D I; excluding these components resulted in values of $N(\mathrm{D\ I})$ which are within the error quoted (although the match to the observed profiles was naturally worse).

We note in passing that $b = 14.6\,\mathrm{km\ s^{-1}}$ (Table 1) corresponds to $b_{\mathrm{th}} = 13.7\,\mathrm{km\ s^{-1}}$ for our assumed $b_{\mathrm{turb}} = 5.0\,\mathrm{km\ s^{-1}}$ (since $b_{\mathrm{th}} \gg b_{\mathrm{turb}}$, very similar values of b_{th} are obtained for all possible values of b_{turb}, from 0 to $5.7\,\mathrm{km\ s^{-1}}$). The implied temperature of the H I gas, $T = m\,b^2/2k$ where m is the atomic mass and k is Boltzmann constant, is $T = 11\,300$ K. This value is essentially the same as that deduced in an analogous way by O'Meara et al. (2001) in their determination of the abundance of D in the $z_{\mathrm{abs}} = 2.536$ sub-DLA ($N(\mathrm{H\ I}) = 2.65 \times 10^{19}\,\mathrm{cm^{-2}}$) toward the QSO HS 0105+1619. Temperatures of $\sim 10^4$ K may appear rather high for H I gas. However, it is now well established that high-z DLAs have far higher spin temperatures (deduced by comparing 21 cm and Lyman α absorption) than H I clouds in the Milky Way. The recent comprehensive compilation of values of T_s by Kanekar & Chengalur (2001) includes eight DLAs with *lower limits* ranging from $T_s > 800$ K to $T_s > 4700$ K. Both the DLA considered here and the one studied

[3]As appropriate to the high ionization gas traced by the Si IV and C IV lines in this DLA

by O'Meara et al. (2001) have metallicities $Z \lesssim 1/100 Z_\odot$. In this regime the low cooling rate from metals may well result in interstellar H I temperatures as high as 10^4 K. Alternatively, the relatively large velocity dispersions deduced by ourselves and O'Meara et al. (2001) may be indicative of the presence of additional absorption components, but in this case it would be a coincidence that both DLAs yield similar values of T. We stress again, however, that the value of N(D I) derived above does not depend on the precise details of the velocity structure of the absorber because the lines most sensitive to N(D I), Ly9 and Ly12, are both on the linear part of the curve of growth.

4. The Column Density of H I and the Abundance of Deuterium

Figure 4 shows the normalised spectrum of Q2206−199 in the region near 3740 Å, which encompasses the damped Lyman α line at $z_{\rm abs} = 2.07623$. This spectrum was obtained by Pettini et al. (in preparation) as part of a program to study the abundances of N and O in DLAs. The profile of the DLA is best fitted with a column density $N(\mathrm{H\ I}) = 2.73 \times 10^{20}\,\mathrm{cm}^{-2}$ (top panel of Figure 4). VPFIT returned a formal error σ_N of less than 1%. Even though the strong Lyman α line is relatively unblended, we consider this estimate to be over-optimistic. The main source of error here is probably the continuum placement *within* the damped line (from ~ 1200 to ~ 1235 Å—see Figure 4); various trials with different interpolations across this wavelength interval showed that $\pm 5 \times 10^{18}\,\mathrm{cm}^{-2}$ is a more realistic assessment of the 1σ error. In any case, the error on N(H I) is clearly much smaller than the error on N(D I) and it is the latter that dominates our measure of D/H. For comparison, the lower resolution and S/N spectrum of Q2206−199 obtained by Pettini et al. (1994), with a different detector and telescope, yielded $N(\mathrm{H\ I}) = (2.7 \pm 0.4) \times 10^{20}\,\mathrm{cm}^{-2}$, in excellent agreement with the value deduced here. Evidently, the column density of neutral gas in this DLA is known with a satisfactory degree of confidence for our present purpose.

From the above measurements we deduce a value of the abundance of deuterium $\mathrm{D/H} = (1.65 \pm 0.35) \times 10^{-5}$; this is the lowest estimate of this ratio obtained up to now.

5. Discussion

At the time when the observations presented here were first proposed, it was still being debated whether the primordial abundance of deuterium was a few times 10^{-5} or one order of magnitude higher (Tytler, Fan, & Burles 1996; Songaila et al. 1995). The controversy is now largely resolved; with several more low values of D/H reported in the last few years, it seems increasingly likely that cases where D/H is apparently greater than 10^{-4} are in reality due to contamination by H I at velocities similar to the isotope shift—always a possibility in the Lyman α forest (e.g. Kirkman et al. 2001). The finding here of a sixth system with low D/H adds further weight to this conclusion.

In Table 2 we have collected published determinations of D/H in QSO absorption line systems at high z; the data are mostly from a similar compilation by O'Meara et al. (2001—their Table 5) augmented by the recent determinations by D'Odorico et al. (2001) and ourselves. The results are plotted in Figure 5. Although the set of measurements is still very limited, we comment on two points of potential interest.

All six absorbers are low metallicity systems, with abundances (as measured by Si) less than 1/30 of solar ([Si/H] < -1.5). We do *not* believe that Figure 5*a* shows a trend of decreasing D/H with increasing [Si/H]. The main reason is that in a closed-box model of chemical evolution a metallicity $Z = -1.5$ is reached when, to a rough approximation, only 3% of the gas has been processed through stars—and only 3% of the deuterium has been destroyed. Thus an increase in metal abundances from -2.5 to -1.5 should result in an imperceptible decrease in the D/H ratio through astration. An additional consideration to be aware of is that not all measurements of [Si/H] in Figure 5*a* are equally reliable. While the metallicities of the three DLAs (squares) are reasonably secure, the estimates in the three LLS (triangles) rely on much larger ionization corrections to account for unobserved ion stages. Thus one should be wary of any apparent correlation of D/H with Z when results from LLS and DLAs are mixed together.

For these reasons it has been assumed until now that in all the cases listed in Table 2 we are measuring the primordial abundance of deuterium and that the dispersion between values found in different QSO absorbers is just due to observational error. Thus, Tytler et al. (2000) and O'Meara et al. (2001) proposed averaging the available determinations to obtain (in the latter, more recent work) a most likely value D/H $= (3.0 \pm 0.4) \times 10^{-5}$.

On the other hand, it is interesting that all three DLAs give consistently lower values of D/H than the three LLS (Figure 5*b*). In general DLAs allow a more accurate measure of the column density of H I than LLS; the shape of the damping wings and the core of the Lyman α line normally constrain the allowed values of N(H I) to a narrow range. This is not always the case for LLS where N(H I) relies more sensitively on the accuracy of the extrapolation of the QSO continuum near the Lyman limit and on the details of the velocity structure of the H I gas giving rise to saturated Lyman series lines. To illustrate this point, we note that in PKS 1937$-$1009 the initial measure $N(\text{H I}) = (8.7 \pm 1.2) \times 10^{17}\,\text{cm}^{-2}$ by Tytler, Fan, & Burles (1996) was later revised by Burles & Tytler (1997) down to $N(\text{H I}) = (7.2 \pm 0.3) \times 10^{17}\,\text{cm}^{-2}$, while a different analysis (Songaila, Wampler, & Cowie 1997) proposed $N(\text{H I}) < 5 \times 10^{17}\,\text{cm}^{-2}$. In Q1009+299 there is the additional problem of partial contamination of the D I absorption by unrelated H I (Burles & Tytler 1998); this is usually less of a concern in the higher column density damped systems.

We do not intend to be critical of these excellent analyses which have taken great care to account for all the relevant factors and arrived at the best estimates allowed by the data. Here we simply speculate, on the basis of the apparent trend in Figure 5*b*, that D/H may have been *over*estimated in the two LLS where deuterium has been detected so far, possibly through an *under*estimate of the column density of neutral hydrogen, and that the most reliable measure of the primordial D/H may in fact be provided by the three damped Lyman α systems, where N(H I) is most secure. Clearly this conjecture will be tested by future observations of additional DLAs; nevertheless, it is worthwhile considering briefly its implications, should it turn out to be correct.

From the three DLAs in Table 2 we obtain a weighted mean:

$$\mathrm{D/H} = (2.2 \pm 0.2) \times 10^{-5} \tag{1}$$

where the weights used are inversely proportional to the square of the error on each measurement and 0.2×10^{-5} is the 1σ error on the weighted mean. Using the analytic expression by Burles, Nollett, & Turner (2001), the primordial abundance of deuterium in eq. (1) implies a baryon-to-photon ratio:

$$\eta = (6.8 \pm 0.4) \times 10^{-10} \tag{2}$$

which in turn yields a baryon density

$$\Omega_B h^2 = 0.025 \pm 0.001 \tag{3}$$

using the scaling of $\Omega_B h^2$ with η given by Burles et al. (2001).

We note that a primordial abundance of deuterium as low as $\mathrm{D/H} = (2.2 \pm 0.2) \times 10^{-5}$ can still be reconciled with the present-day value $(\mathrm{D/H})_{\mathrm{ISM}} = (1.6 \pm 0.1) \times 10^{-5}$ in the Galactic interstellar medium (Tytler et al. 2000 and references therein), particularly when the unrealistic (for the Milky Way at least) assumption of closed-box chemical evolution is relaxed to include outflows and infall of unprocessed gas (e.g. Edmunds 1994; Tosi et al. 1998). It is also possible that $(\mathrm{D/H})_{\mathrm{ISM}}$ is less than 1×10^{-5}, given two recent lower determinations (Vidal-Madjar et al. 1998; Jenkins et al. 1999). Turning to other light elements produced in the Big Bang, the value of η in eq. (2) implies a primordial ^{4}He abundance $Y_P = 0.249$ which is still within the range of current estimates (Pagel 2000), but a high value of the primordial $\mathrm{Li/H} = 6.0 \times 10^{-10}$ which exacerbates the well-known lithium problem (Ryan et al. 2000; Burles et al. 2001).

In the last few months there has been considerable discussion of a possible conflict between the values of Ω_B deduced from the abundances of the light elements interpreted within the framework of Big-Bang nucleosynthesis on the one hand, and from the analysis of the angular power spectrum of the CMB on the other. Recent measurements of the latter have been analyzed to give a best fitting

$$\Omega_B h^2 \simeq 0.032^{+0.005}_{-0.004} \tag{4}$$

where the error is again 1σ (Jaffe et al. 2001). The 2σ difference from the baryon density implied by existing measurements of D/H as summarized by Tytler et al. (2000) and O'Meara et al. (2001) has prompted (not for the first time) speculations that 'new physics'—or at least previously unaccounted for processes (e.g. Naselsky et al. 2001)—may be required to reconcile these two determinations. On the other hand, if the low values of D/H found in damped Lyman α systems are indeed representative of the true primordial abundance of D, as speculated here, the apparent conflict is reduced considerably. The two estimates in eqs. (3) and (4) are nearly within 1σ of each other and the history of astronomical measurements teaches us that 1σ errors almost invariably turn out to be over-optimistic in the light of subsequent improvements in the data.

The key question is whether the systematically low values of D/H in the three DLAs in Figure 5 are a significant result or just a statistical accident. This question can only be answered by more observations of DLAs with the characteristics required to detect and measure D I absorption. Fortunately the prospects for finding such valuable test cases are excellent, given the spectacular increase in the numbers of known QSOs brought about by large-scale searches such as the Sloan digital sky survey and 2dF QSO survey. A significant investment in observing time will be required to follow up these QSOs with higher resolution spectroscopy. However, it is now clear that only by assembling a moderately large sample of D/H measurements at high redshift will it be possible to differentiate between systematic and random errors and eventually determine the primordial abundance of deuterium.

6. Epilogue

Since this paper was submitted for publication there have some important developments of relevance to the discussion above. Three new estimates of Ω_B have been announced, all based on observations of the CMB power spectrum. From the analysis of the full dataset of the BOOMERANG experiment, Netterfield et al. (2001) and de Bernardis et al. (2001) deduced $\Omega_B h^2 = 0.021^{+0.004}_{-0.003}$ (1σ errors). The first results from the Degree Angular Scale Interferometer (DASI) also give $\Omega_B h^2 = 0.022^{+0.004}_{-0.003}$ (Pryke et al. 2001). A new treatment of the MAXIMA-I measurements favours a value which is higher, $\Omega_B h^2 = 0.0325 \pm 0.007$, but still consistent with the other two within the errors (Stompor et al. 2001). Thus one could reasonably argue that the 'problem' has been solved and that Ω_B is now known to within $\sim 10\%$, since the weighted average of all five detections in Table 2, D/H $= (2.6 \pm 0.2) \times 10^{-5}$, implies $\Omega_B h^2 = 0.022 \pm 0.001$, in excellent agreement with the latest CMB mesurements. It just remains to be seen how this newly found concordance stands the test of future measurements.

A second recent development is the re-analysis by Levshakov et al. (2001) of the absorption lines in the $z_{\rm abs} = 3.0249$ DLA in Q0347−383 previously studied by D'Odorico et al. (2001). By including in the complex velocity structure of this DLA a narrow ($b = 3\,{\rm km\ s}^{-1}$) component whose presence is suggested by S II and H_2 absorption lines, Levshakov et al. propose that the abundance of D should be revised upwards from (D/H) $= (2.25 \pm 0.65)\ \times 10^{-5}$ (the value derived by D'Odorico et al. and quoted in Table 2) to (D/H) $= (3.2 \pm 0.4)\ \times 10^{-5}$. If this is indeed the case, then the evidence for a systematic difference in the values of (D/H) between Lyman limit and damped Lyman α systems is made significantly weaker. As emphasized above, only further searches for D in absorption systems with a *simple* velocity structure, such as that presented here, will clarify this point.

In any case, as far as primordial nucleosynthesis is concerned, one of the most urgent goals now is identifying the origin of the dispersion in the values of D/H in Table 2 and Figure 5. The simplest explanation is that the errors of the individual measurements have been underestimated. However, it is worrying that a similarly wide dispersion in D/H can be found in the local ISM, where the factor of ~ 2 variation indicated by earlier work (Sonneborn et al. 2000 and references therein) is apparently confirmed by the latest, high precision, observations with the *Far Ultraviolet Spectroscopic Explorer* (Moos et al. 2001). At both high and low redshift, we do not have a satisfactory explanation for differing D/H ratios in gas of similar chemical composition. Resolving this puzzle is important for two reasons. First, it dents our confidence in the general framework of Big-Bang nucleosynthesis. Second, it thwarts future attempts to use the abundance of D, together with those of elements which are manufactured—rather than destroyed—by stars, to track the chemical evolution of galaxies over the age of the universe. Such attempts seem somewhat futile at present given that the total amount of astration of D over the Hubble time is comparable to the scatter in the determination of D/H at any redshift.

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Table 1. BEST FITTING PARAMETERS FOR H I and D I ABSORPTION AND 1σ ERRORS

Ion	N (cm^{-2})	b (km s^{-1})	z
H I	$(2.73 \pm 0.05) \times 10^{20\,a}$	14.6 ± 0.2^{b}	2.076234 ± 0.000002
D I	$(4.5 \pm 1) \times 10^{15}$	10.6^{c}	2.076234^{d}

[a]Determined from the profile of the damped Lyman α line

[b]The Doppler parameter b has both thermal and turbulent components ($b^2 = b^2_{\rm th} + b^2_{\rm turb}$); $b_{\rm turb}$ was fixed at 5 km s^{-1} (see text)

[c]Fixed to be $b(\text{D I})^2 = b^2_{\rm turb} + 1/2 \times b_{\rm th}(\text{H I})^2$

[d]Fixed to be the same as z(H I)

Table 2. SUMMARY OF D/H MEASUREMENTS AT HIGH REDSHIFT

QSO	$z_{\rm abs}$	N(H I) (cm^{-2})	[Si/H]^{a}	(D/H)$\pm 1\sigma$ (10^{-5})	Ref.
Q0130−403	2.799	4.6×10^{16}	-2.6	< 6.8	O'Meara et al. (2001)
Q1009+299	2.504	2.5×10^{17}	-2.53	4.0 ± 0.65	O'Meara et al. (2001)
PKS 1937−1009	3.572	7.2×10^{17}	-2.26	3.25 ± 0.3	O'Meara et al. (2001)
HS 0105+1619	2.536	2.6×10^{19}	-2.0^{b}	2.5 ± 0.25	O'Meara et al. (2001)
Q2206−199	2.0762	2.73×10^{20}	-2.23^{c}	1.65 ± 0.35	This paper
Q0347−383	3.025	4.3×10^{20}	-1.53^{d}	2.25 ± 0.65	D'Odorico et al.(2001)

[a]In the usual notation, [Si/H] = log(Si/H) − log(Si/H)$_\odot$. We chose Si as an indicator of the overall metallicity Z because this is the element for which most measurements are available for the absorption systems considered here

[b]This is actually [O/H]. The upper limit [Si/H] < -1.85 determined by O'Meara et al. (2001) is consistent with the oxygen abundance

[c]Prochaska & Wolfe (1997)

[d]Prochaska & Wolfe (1999)

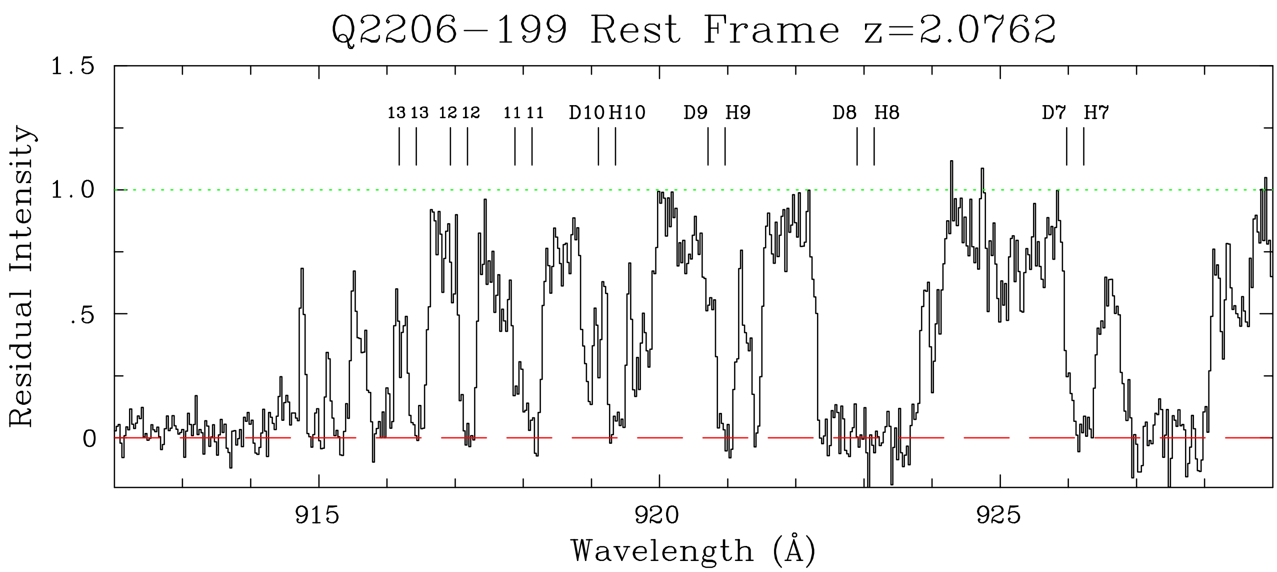

Fig. 1.— Near-UV (2805.5–2857.8 Å) STIS spectrum of Q2206−199 normalised to the QSO continuum and reduced to the rest frame of the $z_{\rm abs} = 2.0762$ DLA. The spectral resolution is 20 km s^{-1} FWHM and S/N $\simeq$ 10; the total exposure time was 82 490 s. The locations of high order Lyman lines of H I and D I, from Ly7 to Ly13, are indicated by vertical tick marks above the spectrum.

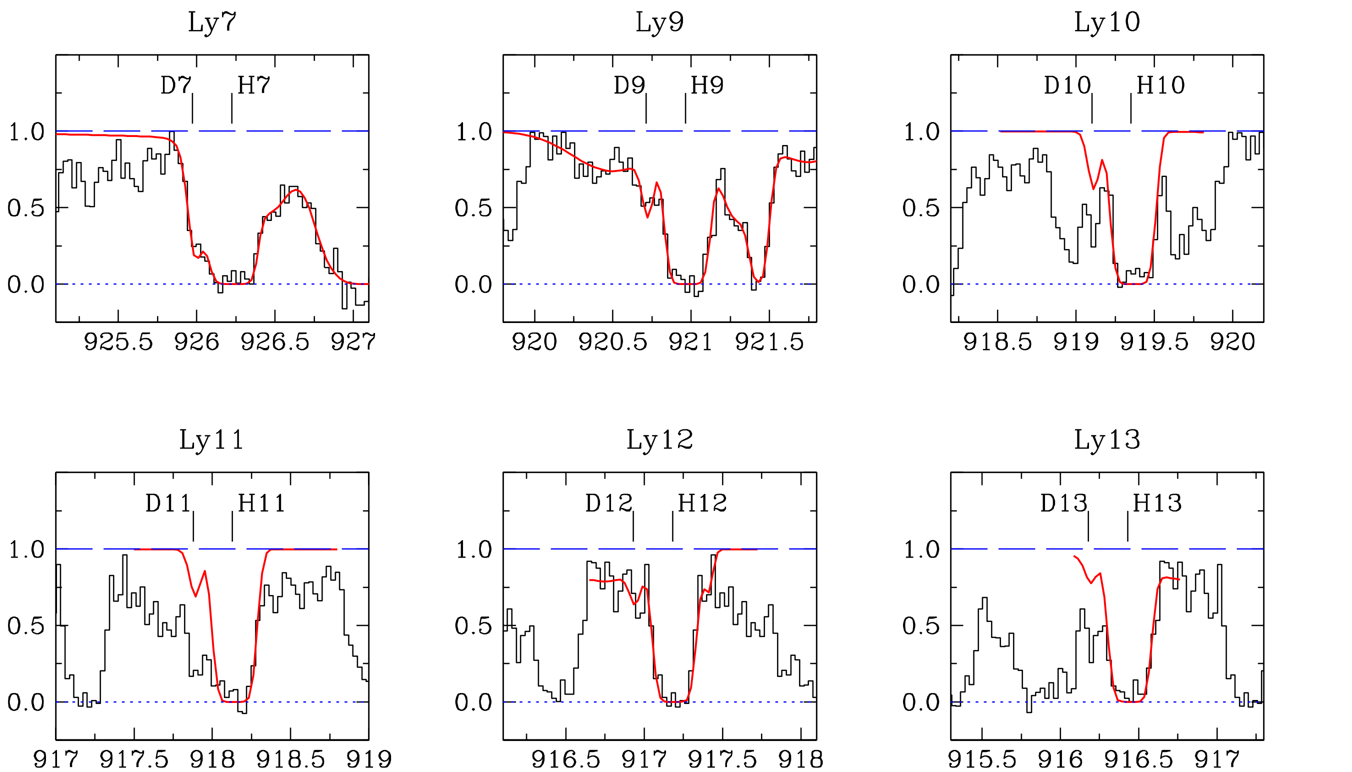

Fig. 2.— Residual intensity vs. rest wavelength (Å) for high order Lyman lines in the $z_{\rm abs} = 2.0762$ DLA. The histograms are the data, while the thin continuous lines show the theoretical absorption profiles for H I and D I corresponding to the best fit solution returned by VPFIT (see Table 1). The important lines here are Ly7, Ly9, and Ly12 which are sufficiently free of contamination to allow a determination of the column density of D I. The fits shown for these three lines include adjacent, unrelated, absorption features. For Ly10, Ly11, and Ly13 we show only the contributions of the H I and D I components to the complex blends present near their wavelengths. Although there is absorption at the expected position of D I in each of these lines, the blends in these three cases are *dominated* by contaminating features, as evidenced by the fact that the optical depths do not match the relative f-values of Ly10, Ly11, and Ly13.

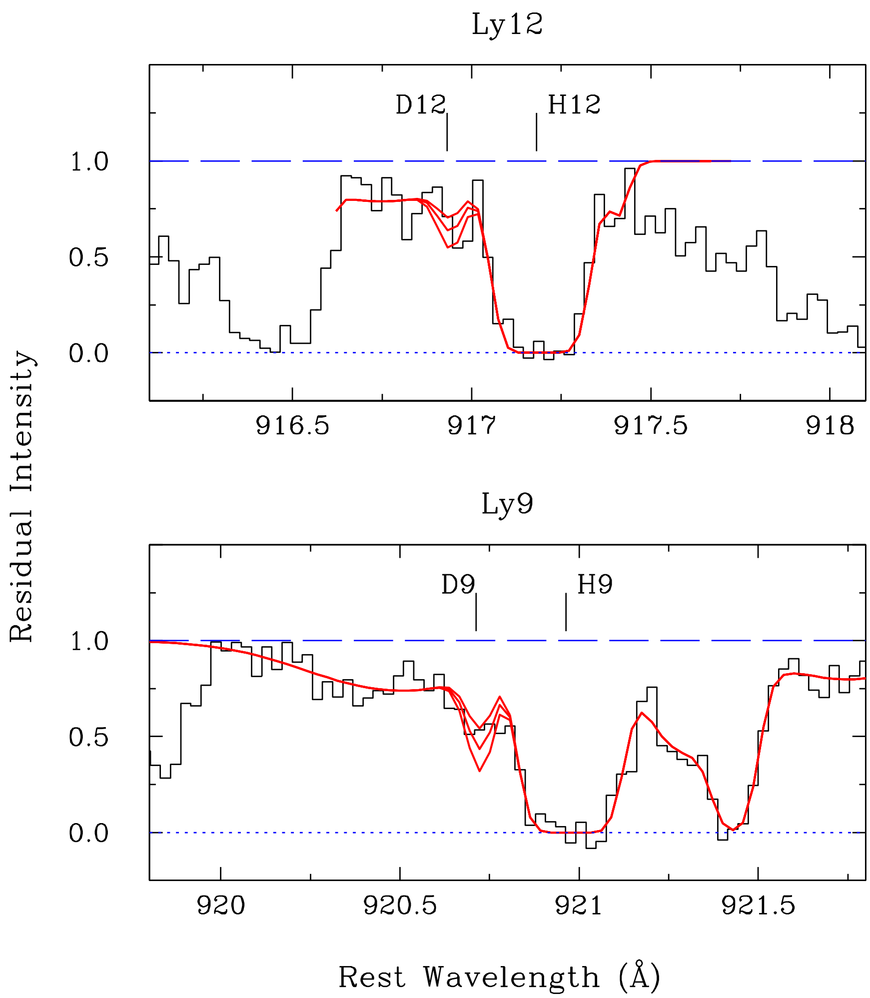

Fig. 3.— Comparison between observed (histogram) and computed (continuous line) profiles for $\log N(\mathrm{D\ I}) = 15.65 \pm 0.2$. This range corresponds to *twice* the 1σ error on $N(\mathrm{D\ I})$ returned by VPFIT.

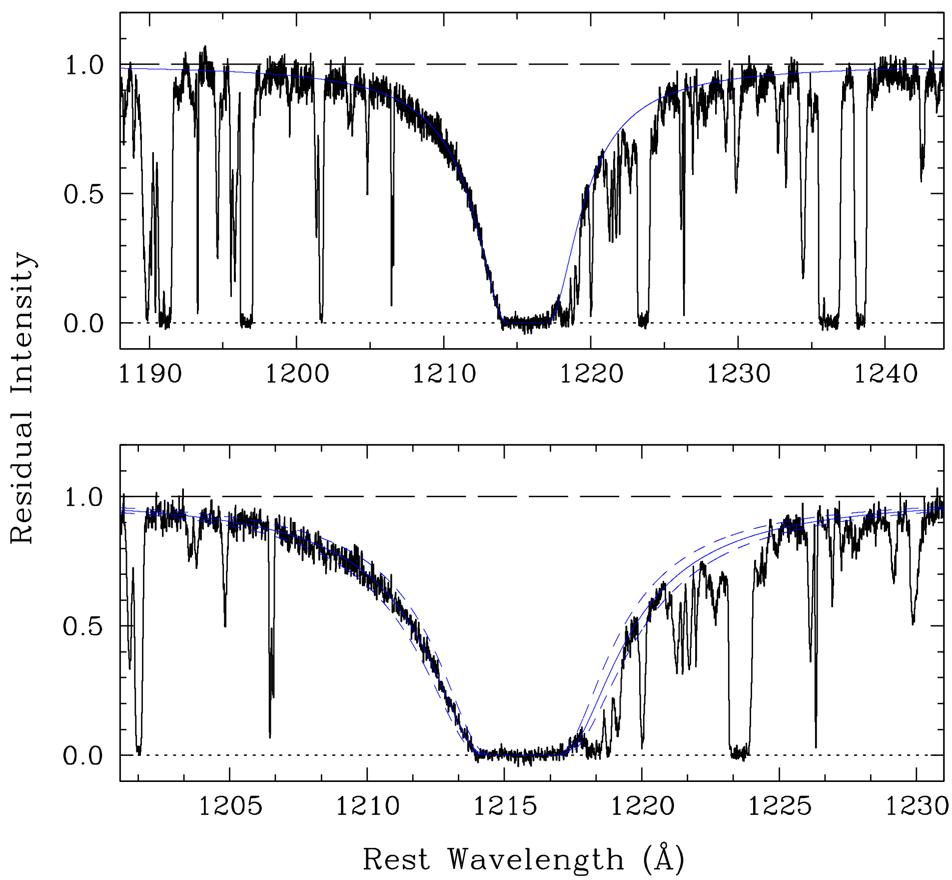

Fig. 4.— Damped Lyman α line in the $z_{\rm abs} = 2.0762$ DLA in Q2206−199 obtained with UVES on the VLT (reproduced from Pettini et al. in preparation). The resolution is $7\,{\rm km\ s}^{-1}$ FWHM. The fit shown in the top panel is for N(H I) $= 2.73 \times 10^{20}$ cm^{-2}. The lower panel shows the damped line on an expanded scale together with three fits, corresponding to N(H I) $= (2.73 \pm 0.5) \times 10^{20}$ cm^{-2}. The range shown corresponds to 10 times the estimated error on N(H I).

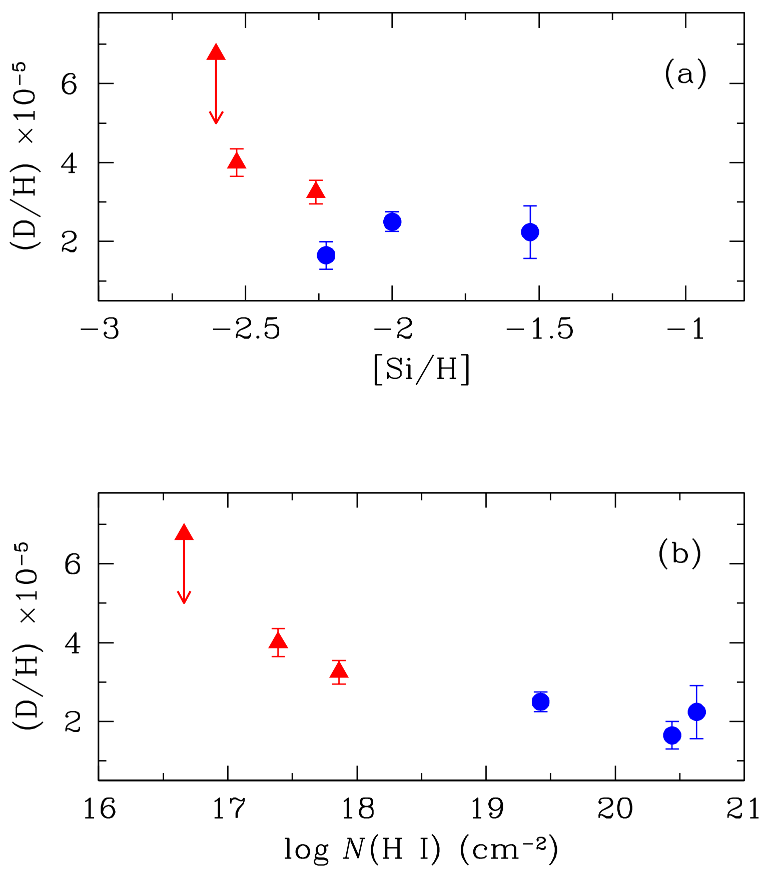

Fig. 5.— Available measurements of the abundance of deuterium in QSO absorption systems at high redshift from Table 2—*triangles:* Lyman limit systems; *circles:* damped Lyman α systems. The top panel shows D/H as a function of metallicity, as measured by the [Si/H] ratio. In the lower panel the deuterium abundance is plotted against the column density of neutral gas. Damped Lyman α systems seem to yield systematically lower values of D/H than Lyman limit systems.